

Mass of the ρ^0 meson in ultra-relativistic heavy-ion collisions

Alejandro Ayala

*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México,
Apartado Postal 70-543, México Distrito Federal 04510, México.*

Jesús Guillermo Contreras

*Departamento de Física Aplicada, Centro de Investigación y Estudios Avanzados,
Unidad Mérida, Apartado Postal 73 Cordemex, Mérida Yucatán 97310, México.*

J. Magnin

Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150 - URCA CEP 22290-180 Rio de Janeiro Brazil.

We study the behavior of the ρ vector mass in the context of the almost baryon-free environment of an ultra-relativistic heavy-ion collision. We show that ρ scattering within the hadronic phase of the collision leads to a temperature dependent, decrease of its intrinsic mass at rest, compared to the value in vacuum. The main contributions arise from s -channel scattering with pions through the formation of a_1 resonances as well as with nucleons through the formation of even parity, spin $3/2$ $[N(1720)]$ and $5/2$ $[\Delta(1905)]$ nucleon resonances. We show that it is possible to achieve a shift in the intrinsic ρ^0 mass of order ~ -40 MeV, when including the contributions of all the relevant mesons and baryons that take part in the scattering, for temperatures between chemical and kinetic freeze-out.

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I. INTRODUCTION

In-medium modifications to the ρ vector meson properties have long been sought after as a probe of the changes experienced by strongly interacting matter with increasing density and/or temperature in collisions of heavy-ions at high energies. The special role played by this meson is due to its short lifetime ($\tau \sim 1.3\text{fm}$) compared to the lifetime of the system ($\sim 10\text{fm}$) formed in the collision.

One possible approach is to study the ρ electromagnetic decay channels. These have the advantage of allowing the reconstruction of the ρ spectrum by looking at particles with a small interaction probability with the surrounding hadronic medium. In this context, the low-mass dilepton spectra have been intensively studied in experiments from BEVALAC/SIS to SPS energies [1]. Nonetheless, in spite of the success of various models [2] that are able to reproduce the main features of the spectra, it is fair to say that the experimental results are thus far inconclusive with regards to the strength of the modifications of the ρ mass and width. Part of the problem with this approach is that, by looking at dileptons that are continuously produced during the different stages of the reaction, one is in fact looking at the changes in the properties of the ρ meson in a time integrated manner, lasting over the whole evolution of the system, which makes it difficult to distinguish the origin and magnitude of such changes.

An alternative approach is to study the ρ hadronic decay channels during the last stage of the collision, namely, during kinetic freeze-out. This kind of probe permits us to look at the decay, regeneration and re-scattering of the meson within a dilute enough hadronic system over a short interval of time, of the order or slightly larger

than the lifetime of the meson. Recently, the advent of large multiplicity events at RHIC energies has made it possible to undertake such measurements. In fact, the STAR collaboration has reported a shift of ~ -40 MeV and ~ -70 MeV for the peak of the invariant mass distribution of the decay $\rho^0 \rightarrow \pi^+\pi^-$ in minimum bias p + p and peripheral Au + Au collisions, respectively, at $\sqrt{s_{NN}} = 200$ GeV as compared to the vacuum value [3].

Given the resonance nature of the ρ meson, changes in the properties of the distribution of its decay products within a thermalized medium with respect to vacuum can be generically divided into phase space distortions of the decay products and intrinsic changes in the properties (mass and width) of the resonance in the heat bath [4, 5]. The quantitative description of the latter is inevitably linked to model dependent considerations. Such models are built to represent the interactions of ρ mesons with other mesons and with baryons. Based on general grounds, these models are made to respect the basic symmetries of the strong interaction, among them, current conservation and parity invariance. Thermal modifications to the ρ intrinsic properties are computed by evaluating the one-loop modification of its self-energy. Attention is paid to those hadrons whose rest mass is near the threshold for s or t channel resonance formation and with a sizable coupling to ρ and to the most abundant particles in the hadronic phase of the collision, namely pions/kaons and nucleons. The phenomenological coupling constants are evaluated by comparing the model prediction of the vacuum decay rate, into the given channel, with the experimentally measured branching ratio.

Recall that the self-energy Π is related to the intrinsic ρ properties by $\text{Im } \Pi = -M_\rho \Gamma^{\text{tot}}$, $M_\rho = \sqrt{m_\rho^2 + \text{Re } \Pi}$,

R	J^P	$\Gamma_{\rho N}^{\text{vac}}(\text{MeV})$	$\Gamma_{\text{tot}}^{\text{vac}}(\text{MeV})$	f_{JP}	$f_{JP}^{\text{N-R}}$
$N(1520)$	$3/2^-$	25	120	9.7	7
$N(1720)$	$3/2^+$	100	150	7	7.8
$\Delta(1700)$	$3/2^-$	120	300	4.4	5
$\Delta(1905)$	$5/2^+$	210	350	12.9	12.2

TABLE I: List of baryon resonances included in the calculation. The last column corresponds to the values of the coupling constants for a non-relativistic (N-R) calculation as computed in Ref. [10].

where m_ρ is the mass of ρ in vacuum, M_ρ and Γ^{tot} are the (temperature and/or density dependent) intrinsic mass and total decay width of the ρ meson, respectively.

Although temperature driven modifications to intrinsic properties of ρ have been thoroughly worked out from interactions with mesons [6], the case of interactions with baryons has mainly been given attention by looking at changes caused by dense nuclear matter effects (see however Refs. [7]) and by means of non-relativistic approximations for the interaction Lagrangians [8, 9, 10].

In this work, we compute the changes to the intrinsic mass of the ρ meson as a function of temperature by considering its scattering off pions/kaons and nucleons in a thermalized hadronic medium, such as the one that is expected to be produced during the dilute, almost baryon free, last stage of an ultra-relativistic heavy-ion collision. To describe all the interactions of ρ we use a manifestly covariant formalism. We show that there is no need to invoke a drop in the nucleon mass to account for a sizable shift in the intrinsic mass of ρ . We work in the imaginary-time formulation of thermal field theory to compute the one-loop ρ self-energy $\Pi^{\mu\nu}$, when interacting with the relevant hadrons. For definitiveness, we take the \hat{z} axis as the direction of motion of the ρ meson and thus the square of its thermal mass can be computed from the thermal part of the component Π^{11} of the ρ self-energy, in the limit of vanishing three-momentum [11]. In this letter, we present only the main lines of thought and central results reserving the details of the calculation to be reported elsewhere.

II. INTERACTIONS OF ρ WITH NUCLEONS AND BARYON RESONANCES

A look at the review of particle physics [12] reveals the existence of four baryon resonances with rest masses near the sum of the rest masses of ρ and nucleon (N) and with sizable decay rates into the ρ -N channel. These are $N(1520)$, $N(1720)$, $\Delta(1700)$ and $\Delta(1905)$. Table I shows their quantum numbers and branching ratios into the ρ -N channel as well as the values of the coupling constants used in the calculation. These last are computed

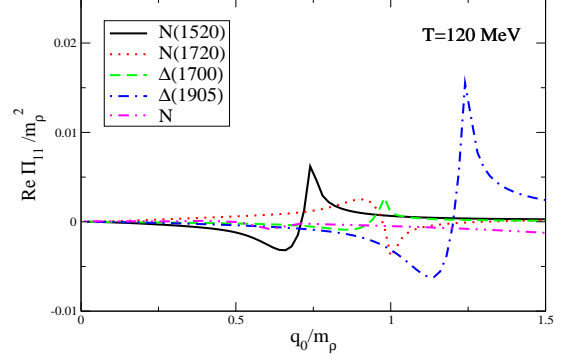


FIG. 1: Contribution to the ρ self-energy from scattering with nucleons and various other nucleon resonances. The main contribution for $q_0 \sim m_\rho$ stems from the formation of s -channel, positive parity spin $3/2$ $N(1720)$ and spin $5/2$ $\Delta(1905)$ resonances.

by adjusting the experimentally measured branching ratios into the ρ -N channel to the theoretical expression for the decay width obtained by using the corresponding interaction Lagrangian. For a reliable estimate of the coupling constants, we include the finite width of ρ by folding the expression for the width at a given ρ mass with the ρ spectral function. For definitiveness, the ρ spectral function is taken as a relativistic Breit-Wigner function

$$S(q) = \frac{2m_\rho \Gamma(q)}{(q^2 - m_\rho^2)^2 + (m_\rho \Gamma(q))^2}, \quad (1)$$

where we also include the proper phase space angular momentum dependence for the ρ decay into two pions [10], taking

$$\Gamma(q) = \Gamma^{\text{vac}} \left(\frac{\sqrt{q^2/4 - m_\pi^2}}{\sqrt{m_\rho^2/4 - m_\pi^2}} \right)^3, \quad (2)$$

where we use $\Gamma^{\text{vac}} = 150$ MeV. For comparison, Table I also shows the values of the coupling constants $f_{JP}^{\text{N-R}}$ obtained by means of a non-relativistic approach [10]. The interaction Lagrangians \mathcal{L} are given by

$$\mathcal{L} = \begin{cases} \frac{f_{3/2^-}}{m_\rho} \mathcal{F}_{\rho N 3/2^-} \bar{\psi}^\mu \gamma^\nu \psi F_{\mu\nu} & \left(J^P = \frac{3}{2}^- \right) \\ \frac{f_{3/2^+}}{m_\rho} \mathcal{F}_{\rho N 3/2^+} \bar{\psi}^\mu \gamma^5 \gamma^\nu \psi F_{\mu\nu} & \left(J^P = \frac{3}{2}^+ \right) \\ \frac{f_{5/2^+}}{m_\rho^2} \mathcal{F}_{\rho N 5/2^+} \bar{\psi}^{\mu\nu} \gamma^5 \gamma^\lambda \psi \partial_\nu F_{\mu\lambda} & \left(J^P = \frac{5}{2}^+ \right) \end{cases} \quad (3)$$

where f_{JP} are the coupling constants between ρ , N and the baryon resonance R , $F_{\mu\nu} = \partial_\mu \rho_\nu - \partial_\nu \rho_\mu$ is the ρ field strength tensor, ψ is the nucleon field, ψ^μ is the spin $3/2$ field and $\psi^{\mu\nu}$ is the spin $5/2$ field [8, 13]. $\mathcal{F}_{\rho NR}$ are hadronic form factors that take into account the finite size of the particles that appear in the effective vertexes. These form factors are taken to be of dipole form

$$\mathcal{F}_{\rho NR} = \left(\frac{2\Lambda^2 + m_R^2}{2\Lambda^2 + s} \right)^2, \quad (4)$$

where s is the energy squared in the system where the resonance R is at rest and Λ is a phenomenological cutoff. The obtained values for the coupling constants do not change when Λ varies in the range $1 \text{ GeV} < \Lambda < 2 \text{ GeV}$ which is a reasonable interval when considering hadronic

processes. All the interactions in Eqs. (3) are current and parity conserving.

To compute the one-loop ρ self-energy we use the generalized Rarita-Schwinger propagators for fields with spin higher than 1/2, given by [8, 14, 15]

$$\mathcal{R}_{3/2}^{\mu\nu}(K) = \frac{(K + m_R)}{K^2 - m_R^2} \left\{ -g^{\mu\nu} + \frac{1}{3}\gamma^\mu\gamma^\nu + \frac{2}{3}\frac{K^\mu K^\nu}{m_R^2} - \frac{1}{3}\frac{K^\mu\gamma^\nu - K^\nu\gamma^\mu}{m_R} \right\} \quad (5)$$

$$\begin{aligned} \mathcal{R}_{5/2}^{\alpha\beta\rho\sigma}(K) = & \sum_{\substack{\rho \leftrightarrow \sigma \\ \alpha \leftrightarrow \beta}} \left\{ \frac{1}{10}\frac{K^\alpha K^\beta K^\rho K^\sigma}{m_R^4} + \frac{1}{10}\frac{K^\alpha K^\beta K^\sigma \gamma^\rho - K^\rho K^\sigma K^\alpha \gamma^\beta}{m_R^3} + \frac{1}{10}\frac{K^\alpha \gamma^\beta K^\sigma \gamma^\rho}{m_R^2} \right. \\ & + \frac{1}{20}\frac{K^\alpha K^\beta g^{\sigma\rho} + K^\sigma K^\rho g^{\alpha\beta}}{m_R^2} - \frac{2}{5}\frac{K^\alpha K^\sigma g^{\beta\rho}}{m_R^2} - \frac{1}{10}\frac{\gamma^\sigma K^\beta g^{\alpha\rho} - \gamma^\alpha K^\sigma g^{\beta\rho}}{m_R} \\ & \left. - \frac{1}{10}\gamma^\alpha \gamma^\sigma g^{\beta\rho} - \frac{1}{20}g^{\alpha\beta} g^{\sigma\rho} + \frac{1}{4}g^{\alpha\rho} g^{\beta\sigma} \right\} \frac{(K + m_R)}{K^2 - m_R^2} \end{aligned} \quad (6)$$

where m_R is the mass of the resonance and the sum over the indexes $\alpha\beta\rho\sigma$ of a tensor $T^{\alpha\beta\rho\sigma}$ means

$$\sum_{\substack{\rho \leftrightarrow \sigma \\ \alpha \leftrightarrow \beta}} T^{\alpha\beta\rho\sigma} \equiv T^{\alpha\beta\rho\sigma} + T^{\beta\alpha\rho\sigma} + T^{\alpha\beta\sigma\rho} + T^{\beta\alpha\sigma\rho}. \quad (7)$$

In order to ensure that the unphysical spin-1/2 degrees of freedom contained in ψ^μ and $\psi^{\mu\nu}$ have no observable effects even in the interacting theories described by Eqs. (3), the propagators in Eqs. (5) and (6) have to be regarded as the leading order terms in an expansion in the parameter $1/m_B$ where m_B is the (heavy) baryon mass [15].

We also include the contribution from interactions between ρ and nucleons given by

$$\mathcal{L}_{\rho NN} = f_{\rho NN} \bar{\psi} \left(\gamma^\mu - \frac{\kappa}{2m_N} \sigma^{\mu\nu} \partial_\nu \right) \rho_\mu \psi \quad (8)$$

where $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$, m_N is the mass of the nucleon and we take the values of the dimensionless coupling constants $f_{\rho NN}$ and κ as $f_{\rho NN} = 2.63$ and $\kappa = 6.1$ [16].

For the interaction Lagrangians in Eqs. (3), the calculation involves the sum two Feynman diagrams whose corresponding expressions, written in Minkowski space are

$$\begin{aligned} \Pi_{(J)\mu\nu}^{\pm(a)} &= IF \int \frac{d^4 p}{(2\pi)^4} \frac{T_{(J)\mu\nu}^\pm(P, P+Q)}{[P^2 - m_N^2][(P+Q)^2 - m_R^2]} \\ \Pi_{(J)\mu\nu}^{\pm(b)} &= IF \int \frac{d^4 p}{(2\pi)^4} \frac{T_{(J)\mu\nu}^\pm(P, P-Q)}{[P^2 - m_N^2][(P-Q)^2 - m_R^2]} \end{aligned} \quad (9)$$

where \pm refer to the case of interactions with positive and negative parity baryon resonances, respectively, IF

is the isospin factor and

$$\begin{aligned} T_{(3/2)\mu\nu}^\pm(P, K) &= \text{Tr}[(P + m_N) \Gamma_{\mu\alpha}^\pm \mathcal{R}_{3/2}^{\alpha\beta}(K) \Gamma_{\beta\nu}^\pm] \\ T_{(5/2)\mu\nu}^\pm(P, K) &= \text{Tr}[(P + m_N) \Gamma_{\mu\alpha\beta}^\pm \mathcal{R}_{5/2}^{\alpha\beta\rho\sigma}(K) \Gamma_{\rho\sigma\nu}^\pm] \end{aligned} \quad (10)$$

where the vertices $\Gamma_{\mu\alpha}^\pm$ and $\Gamma_{\mu\alpha\beta}^\pm$, as obtained from the interaction Lagrangians in Eqs. (3), are given by

$$\begin{aligned} \Gamma_{\mu\alpha}^\pm &= \left(\frac{f_{3/2}^\pm}{m_\rho} \right) \mathcal{F}_{\rho N 3/2^\pm} \gamma_5^{(1\pm 1)/2} (\gamma_\mu Q_\alpha - Q_\mu g_{\mu\alpha}) \\ \Gamma_{\mu\alpha\beta}^\pm &= \left(\frac{f_{5/2}^\pm}{m_\rho} \right) \mathcal{F}_{\rho N 5/2^\pm} \gamma_5^{(1\pm 1)/2} \gamma_\delta Q^\beta \\ &\quad (Q_\alpha g_{\delta\mu} - Q_\mu g_{\delta\alpha}). \end{aligned} \quad (11)$$

Figure 1 shows the temperature dependent real part of Π^{11} scaled to the square of the ρ mass in vacuum, for each of the resonances listed in Table I as a function of q_0/m_ρ , where q_0 is the energy of the ρ meson at rest, for a temperature $T = 120 \text{ MeV}$. Notice that the two terms in Eqs. (9) represent the contribution from nucleons and

R	J^P	ρh decay	$\Gamma_{\rho h}^{\text{vac}}$ (MeV)	$\Gamma_{\text{tot}}^{\text{vac}}$ (MeV)	$g_{\rho h R}$ (GeV) $^{-1}$	IF
$\omega(782)$	1^-	$\rho\pi$	~ 5	8.43	25.8	1
$h_1(1170)$	1^+	$\rho\pi$	seen	~ 360	11.37	1
$a_1(1260)$	1^+	$\rho\pi$	dominant	~ 400	13.27	2
$K_1(1270)$	1^+	ρK	~ 60	~ 90	9.42	2
$\pi'(1300)$	0^-	$\rho\pi$	seen	~ 400	7.44	2

TABLE II: List of meson resonances included in the calculation. The last column corresponds to the isospin factor accounting for the number of isospin channels that take part in the dispersion. The coupling constants are taken from the analysis in Ref. [6].

anti-nucleons to the scattering, as corresponds to the scenario where resonance production happens from the – almost baryon free – central region of the reaction. The isospin factor considered for all these processes has been taken as $IF = 2$. The main contributions in magnitude for $q_0 \sim m_\rho$ come from the resonances with even parity $N(1720)$ and $\Delta(1905)$. We also show the contribution from scattering with nucleons, taking m_N to its vacuum value. Notice that for the kinematical range considered, the contribution from nucleons is completely negligible.

An interesting aspect of the result is the difference in the behavior between the real parts of the contributions of $N(1720)$ and $\Delta(1905)$ to the ρ self-energy as a function of q_0 , the former starting out repulsive and the latter attractive. The reason for this behavior is that, given that these are resonances with different spin, the structure of their propagators and couplings with nucleons is different. The leading term for each case when $q_0 \rightarrow 0$ is of the form $c \cdot q_0$ where c is a numerical coefficient to which several terms from the product of the propagator and vertices contribute. It turns out that this coefficient is positive in the case of $N(1720)$ and negative in the case of $\Delta(1905)$. We emphasize that this conclusion is born out of the explicit calculation. We should however point out that an important cross check of the result, namely, the transversality of the self-energy, has been carried out. This is by no means a trivial check of the consistency of the calculation since had one or more of the terms that make up the above mentioned c coefficient been wrong, the transversality would have been spoiled.

III. INTERACTIONS OF ρ WITH PIONS AND MESONS

We now look at the contribution to the ρ self-energy stemming from scattering with pions and other mesons. Table II shows the quantum numbers of those mesons with sizable branching ratios involving the pion and ρ and whose rest mass is near the sum of the rest masses of the pion/kaon and ρ , as well as the coupling constants used in the calculation. For the interaction of ρ and the pion, π , we take the Lagrangian

$$\mathcal{L} = g_{\rho\pi\pi} \pi (\partial^\mu - i g_{\rho\pi\pi} \rho^\mu) \pi \rho_\mu \quad (12)$$

obtained by *gauging* the pion-pion interaction Lagrangian [11, 17]. The value of the dimensionless coupling constant, as determined by the ρ width in vacuum, is taken as $g_{\rho\pi\pi} = 6.06$ [11].

The interaction Lagrangians involving the other relevant mesons are taken as [6]

$$\mathcal{L} = \begin{cases} g_{\rho PA} \mathcal{F}_{\rho PA} A^\mu \partial^\nu P F_{\mu\nu} \\ g_{\rho\pi V} \mathcal{F}_{\rho\pi V} \epsilon_{\mu\nu\sigma\tau} \partial^\mu \pi V^\nu \partial^\sigma \rho^\tau \\ (g_{\rho\pi P'}/m_\rho) \mathcal{F}_{\rho\pi P'} \partial^\mu \pi \partial^\nu P' F_{\mu\nu} \end{cases} \quad (13)$$

where V^μ and A^μ represent the vector and axial-vector fields and P, P' the pseudo-scalar fields. $\mathcal{F}_{\rho PR}$ are dipole

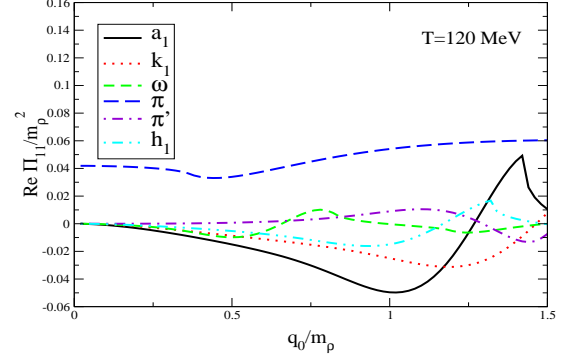


FIG. 2: Contribution to the ρ self-energy from scattering with pions and various other mesons. The main contribution for $q_0 \sim m_\rho$ stems from the formation of an s -channel axial-vector resonance a_1 .

form factors [see Eq. (4)]. The coupling constants $g_{\rho PR}$ in Eqs. (13) are taken from Ref. [6]. The interaction Lagrangians in Eqs. (12) and (13) are current and parity conserving as well as compatible with chiral symmetry.

The expressions for the one-loop ρ self-energy corresponding to the interaction Lagrangians in Eqs. (13), can be written in Minkowski space, as

$$\Pi_{\mu\nu}^{(JP)} = IF \int \frac{d^4 p}{(2\pi)^4} \frac{M_{\mu\nu}^{(JP)}}{[P^2 - m_P^2][(Q - P)^2 - m_R^2]} \quad (14)$$

where m_P is the mass of the pseudoscalar (π or K) and m_R is the mass of the vector, axial-vector or $\pi'(1300)$ and IF is the isospin factor. The numerators in Eq. (14) are given by

$$\begin{aligned} M_{\mu\nu}^{(1\pm)} &= \Gamma_{\mu\alpha}^{(1\pm)} \left(g^{\alpha\beta} - \frac{K^\alpha K^\beta}{m_R^2} \right) \Gamma_{\beta\nu}^{(1\pm)} \\ M_{\mu\nu}^{(0+)} &= \Gamma_\mu^{(0+)} \Gamma_\nu^{(0+)}, \end{aligned} \quad (15)$$

where the vertices, as obtained from the interaction Lagrangians in Eqs. (13) are given by

$$\begin{aligned} \Gamma_{\alpha\beta}^{(1+)} &= g_{\rho PA} \mathcal{F}_{\rho PA} [g_{\alpha\beta}(P \cdot Q) - P_\alpha Q_\beta] \\ \Gamma_{\alpha\beta}^{(1-)} &= g_{\rho\pi V} \mathcal{F}_{\rho\pi V} [\epsilon_{\gamma\alpha\delta\beta}(Q - P)^\gamma Q^\delta] \\ \Gamma_\alpha^{(0+)} &= (g_{\rho\pi P'}/m_\rho) \mathcal{F}_{\rho\pi P'} \\ &\quad [Q \cdot (Q - P) P_\alpha - (P \cdot Q) K_\alpha] \end{aligned} \quad (16)$$

Figure 2 shows the temperature dependent real part of Π^{11} scaled to the square of the ρ mass in vacuum arising from pion exchange as well as each of the mesons listed in Table II as a function of q_0/m_ρ , for a temperature $T = 120$ MeV. We notice that in the interval considered, the main contribution comes from scattering of ρ off pions. However, for $q_0 \sim m_\rho$ a sizable contribution in magnitude comes from π - ρ scattering through the formation of an s -channel axial-vector resonance a_1 , which has the opposite

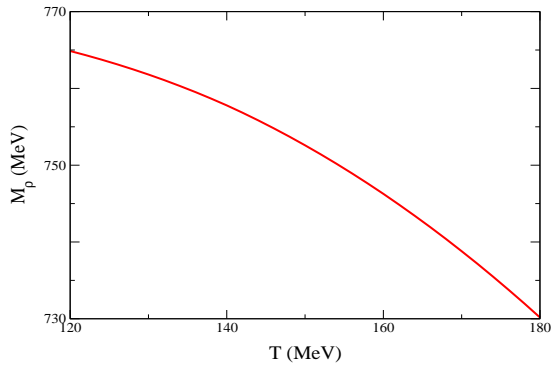


FIG. 3: Intrinsic mass of ρ^0 as a function of temperature.

sign and about the same strength as the contribution from pion exchange, in agreement with the findings in Ref. [6]. Also, for $q_0 \sim m_\rho$, the rest of the contributions offset among themselves.

IV. INTRINSIC MASS OF THE ρ^0

We now put together the contributions from all of the particles considered in Secs. II and III. Figure 3 shows the total shift in the intrinsic ρ mass as a function of temperature. Notice that the shift increases in magnitude as the temperature increases. For instance, taking $m_\rho = 770$ MeV, we get $M_\rho = 764$ – 730 MeV when the temperature varies between $T = 120$ – 180 MeV, which is a reasonable range for the temperature of the hadronic phase of a relativistic heavy-ion collision between chemical and kinetic freeze-out.

We should emphasize that these findings refer to the *intrinsic* changes in the ρ mass. The overall change in the mass of the peak of the invariant $\pi^+ \pi^-$ distribution should contain also the effects of phase-space distortions due to thermal motion of the decay products as well as the effect due to the change in the intrinsic ρ width [4, 18].

V. SUMMARY AND CONCLUSIONS

In this work we have computed the intrinsic changes in the ρ mass due to scattering with the relevant mesons and baryons in the context of ultra-relativistic heavy-ion collisions, at finite temperature. We have found that the contributions from scattering with nucleons through the formation of even parity, spin 3/2 [N(1720)] and 5/2 [$\Delta(1905)$] nucleon resonances are significant.

The different behavior between the real parts of the contributions of N(1720) and $\Delta(1905)$ to the ρ self-energy as a function of q_0 is understood as arising from the different structure of their propagators and couplings with nucleons, given that they are resonances with different spin.

These results underline the importance of scattering of ρ mesons with nucleons at finite temperature for the decrease of the intrinsic mass of ρ , without the need of invoking a drop in the nucleon mass during kinetic freeze-out.

In conclusion, we have shown that it is possible to achieve a shift in the intrinsic ρ^0 mass of up to ~ -40 MeV, when including the contributions of all the relevant mesons and baryons that take part in the scattering, for temperatures within the commonly accepted values between chemical and kinetic freeze-out.

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